Chapter 3
Biomass

Abstract The energy stored in the biomass existing on the Earth can be transformed by chemical or biological processes into heat or electricity. From a certain point of view, biomass can be considered as solar energy stored in carbohydrate chemical bonds by means of the photosynthesis process. Therefore, the emitted CO_2 to the atmosphere, when biomass is burned or transformed, can be considered to be equal to the CO_2 absorbed during its previous growth, i.e., energy from biomass could in principle be considered as carbon neutral. It is important to remark that bioenergy provides about 12 % of the global energy consumption, and therefore is, together with hydropower, one of the main renewable energy resources in the world. In this chapter, we describe some of the most common energy processes for using biomass as a fuel: direct combustion, pyrolysis for the production of charcoal, gasification for obtaining synthesis or producer gas, co-firing with coal, etc. On the other hand, the production of liquid or gaseous biofuels will be treated in Chap. 4.

3.1 Overview

Biomass is any living mass, both animal and vegetable, existing on Earth, including its waste. Biomass can be converted into heat or other energy carriers such as electricity, when it reacts with oxygen in the combustion process. Biomass is almost the only type of fuel used by mankind since ancient times up to the industrial revolution, with large use in wide areas of the less developed world at present.

Biomass has a low energy density compared to fossil fuels. However, its energy density can be increased substantially by conversion to biofuels through different mechanical, chemical or biological procedures. This chapter covers the technological aspects related to solid biomass, which can be partially or totally transformed to a gaseous fuel (biogas), being its energy used as well. On the other hand, Chap. 4 is completely devoted to the technologies related to liquid biofuels.

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Table 3.1 Energy content per unit weight and volume for various types of biomass [1, 2]

Feedstock	GJ/t	GJ/m^3
Dry wood	15	10
Paper	17	9
Dry manure	16	4
Baled straw	14	1.4
Dry sugar cane	14	10
Household waste	9	1.5
Crude	42	34
Coal	18	50
Natural gas	55	0.04

Biomass can also be considered as solar energy stored in chemical bonds of carbon–hydrogen as a result of metabolic activity or photosynthesis of different organisms. Through this process, CO_2, water and some nutrients are converted into biomass, which is mainly composed of carbohydrates, fats, proteins and minerals. About 95 TW (0.05 %) of the solar power that reaches the Earth (170,000 TW) is considered to be absorbed to produce photosynthesis [1, 2].

The energy stored in biomass varies between 8 GJ/t for green wood and 15 GJ/t for dry wood, which are very low compared to 55 GJ/t for natural gas. Table 3.1 [1, 2] shows the energy content of various types of biomass, both per unit weight and volume, and are compared to those of oil, coal and natural gas.

According to statistics from the International Energy Agency [3], the supply of biomass (primary solid biomass, biogas, liquid biofuels and renewable municipal waste) has grown steadily from 26.05 EJ in 1971 to 50.20 EJ in 2009 (last available data) (Fig. 3.1). Of this amount, 93.7 % corresponds to primary solid biomass, biogas 1.9 % and 4.4 % for liquid biofuels. Renewable municipal waste reached 0.59 EJ in 2009.

Only 0.7 EJ of the 50.79 EJ biomass and renewable municipal waste supplied in 2009 has been dedicated to the production of electricity and heat. Although this represents a small percentage of 1.37 %, it has been increasing continuously since 2001 (Fig. 3.2).

The distribution in terms of biomass types dedicated to the production of electricity and heat is shown in Table 3.2. The largest amount is observed for renewable municipal waste, while the percentage of primary solid biomass is minimal, and no liquid biofuels are used for this purpose. However, in absolute terms, the largest amount of biomass dedicated to the production of both electricity and heat comes from primary solid biomass.

If we consider the evolution of electricity and heat production from biomass in recent years, increasing trends are observed in most cases. More specifically, in the case of electricity production, there has been a steady increase in production dominated by solid biomass (Fig. 3.3a). For heat production, it is also solid biomass the one that leads the rankings (Fig. 3.3b).

The global technical potential of biomass is estimated in the literature that could reach 1,500 EJ/year in 2050, but if sustainability criteria are also considered, the potential would be 200–500 EJ/year (excluding aquatic biomass) [4]. Forest,

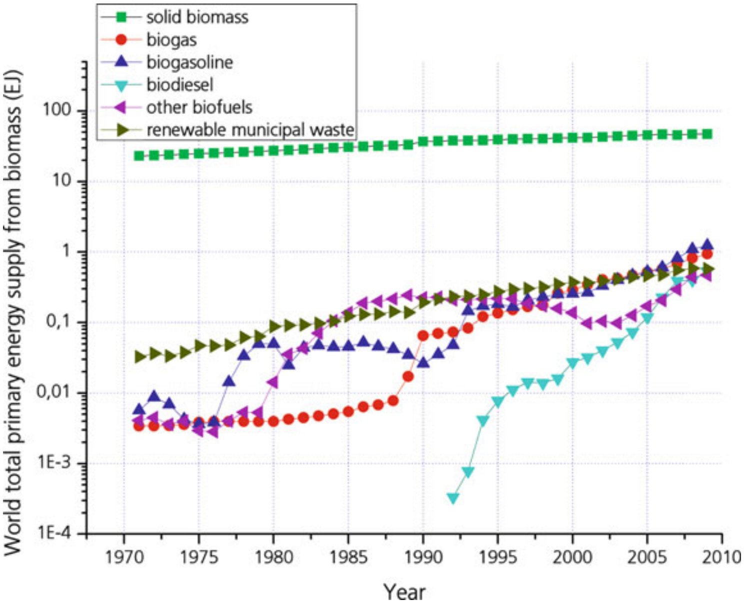

Fig. 3.1 Evolution of total primary energy supply from various types of biomass and renewable municipal waste between 1971 and 2009 [3]

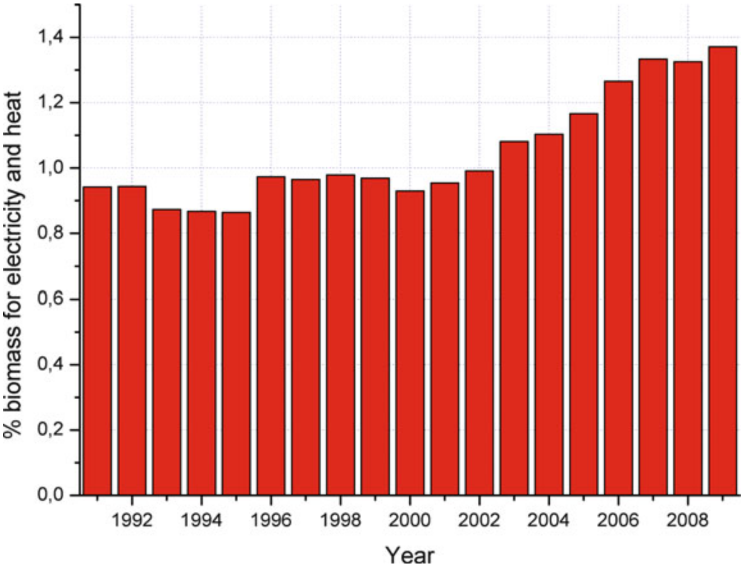

Fig. 3.2 Evolution of the percentage of biomass and renewable municipal waste supplied for the production of electricity and heat during the period 1990–2009

Table 3.2 Energy (EJ) and percentage of biomass, by type, dedicated to the supply of electricity and heat in 2009

2009	Electricity EJ—(%)	Heat EJ—(%)
Primary solid biomass	0.17—(0.37)	0.33—(0.71)
Biogas	0.04—(4.03)	0.01—(1.51)
Renewable municipal waste	0.03—(5.30)	0.10—(18.03)

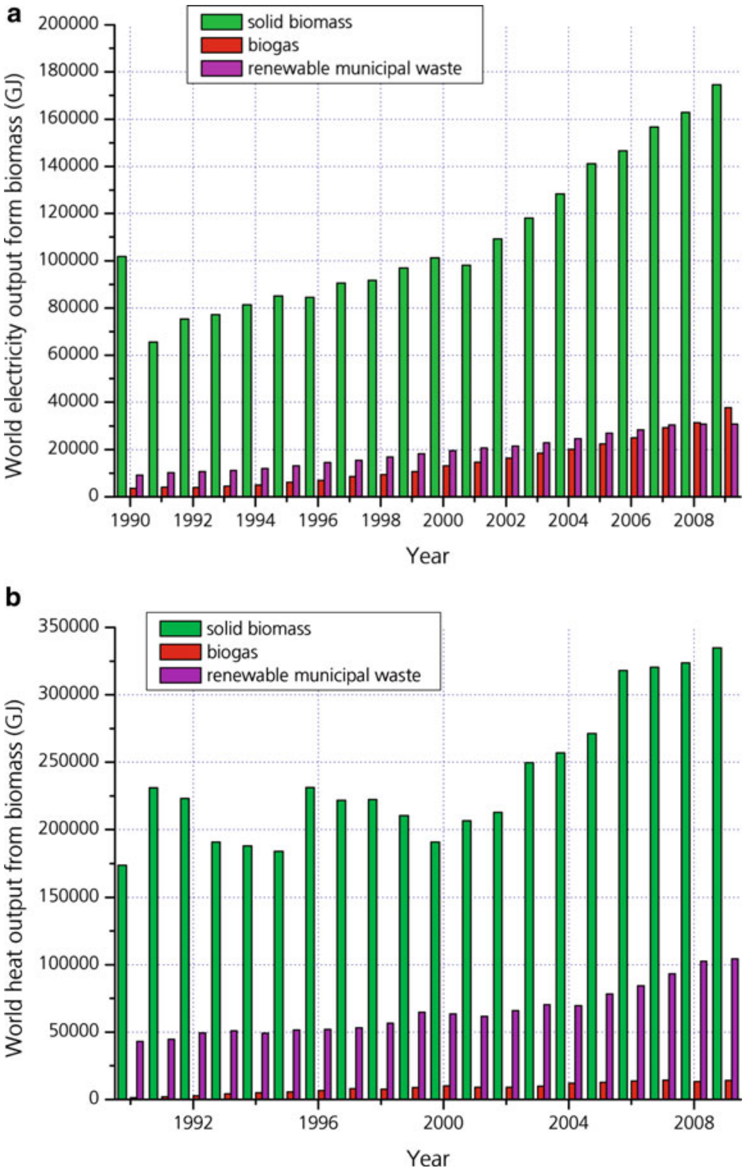

Fig. 3.3 Evolution of the gross production of (**a**) electricity and (**b**) heat from 1990 to 2009 for different types of biomass

agricultural and other waste (including municipal waste) could provide between 50 and 150 EJ/year, while the rest could be obtained from energy crops, forest surplus and increased agricultural productivity [4]. The wide variety of biomass resources at a geostrategic level can also help to improve the security in energy supply.

3.2 State of the Art

Unlike other types of technologies for exploiting renewable sources, biomass is extremely varied in its nature and, consequently, requires specific technologies in each case, both the management of the particular crops, and in the energy use, like heat, electricity, etc.

3.2.1 Energy Crops

Energy crops are receiving increasing attention for several reasons: obtaining alternative fuels to fossil fuels, reducing CO_2 emissions, reaching greater energy independence, use of fallow land, reducing water demand, etc.

Wood forest crops for energy use are obtained from modified forests having a large tree density. The harvest of forest in the short term is made cutting and gathering wood in periods of few years, in locations with favourable annual yield, like in Northern Europe where yields of up to 10 t/ha are reached [1]. The harvested timber is generally used for the production of heat and/or electricity.

To produce bioenergy from agricultural crops, the most widely used plants are sugar cane and corn, as discussed in more detail in next chapter. These plants are used for the production of liquid biofuels. Other plants such as sunflowers and soybeans are used for biodiesel production. Moreover, the yield per hectare of energy crops has grown significantly since 1960 until 2005. Thus, there has been a 70 % increase in production for sugar cane and 400 % increase for corn during this period [5].

Table 3.3 shows both the biomass yield (t/ha) and the energy equivalent produced per hectare and year for different energy crops [2]. It is assumed that the values shown are the maxima obtained in practice and that the biomass is almost dry.

For further comparisons with other energy technologies, the energy efficiency of photosynthesis is defined as the energy content (heat from glucose combustion to CO_2 and liquid H_2O at STP) of the biomass that can be harvested annually divided by the annual solar irradiance over the same area. Then, solar energy conversion efficiencies for crop plants in both temperate and tropical zones typically do not exceed 1 %; for comparison, efficiencies of 3 % are obtained for microalgae grown in bioreactors and about 5–7 % for microalgae in bubbled bioreactors. On the other hand, a theoretical limit of about 12 % can be considered for the efficiency of photosynthetic glucose production from CO_2 and water [6].

Table 3.3 Maximum performance energy harvests from dry biomass [2]

Feedstock	Yield (t/ha)	Energy (GJ/ha)
Forest wood	7	130
Tropical wood	11	200
Sorghum (3 harvest/year)	50	850
Sudan grass (6 harvest/year)	40	600
Corn	25	77
Wheat	22	
Sugar cane	30	150

3.2.2 Cultivation Techniques

The two main aspects to be considered in this section are the availability of land and its productivity. Currently, it is estimated that less than 1 % of agricultural land is dedicated to energy crops [7]. The yield of energy crops depends on many factors such as climate, soil type, available water resources and technology. Profitable performance is considered at 10–12 t of dry biomass per hectare per year, equivalent to an energy yield of 220 GJ/ha [5]. Given that the average amount of solar energy received in 1 year is about 1,000 kWh/m^2, solar energy conversion into bioenergy would reach only 0.6 % efficiency.

The cultivation techniques vary very substantially between countries in terms of cost of labour and access to automation process systems. In general, the productivity of the cultivation process increases with the level of development of the country concerned. Consequently, it is estimated that global productivity can be substantially improved as new cultivation techniques are adopted by the most underdeveloped countries.

3.2.3 Harvesting, Storage and Transportation

Obviously, energy crops, after having been grown, should be harvested, dried, cut and transported. The objective is to obtain a homogeneous product of appropriate size, high energy density and with minimal moisture.

The harvest of forest residues also arises from the cleaning and maintenance of forests and these residues are harvested using similar techniques to those used in forests devoted to energy crops. Currently, however, the larger amount of residues generated in moderate temperature regions are derived from wheat straw and corn. These residues are rarely used but burned in the field. Alternatively, these wheat straw and corn residues can be pressed up to 1 t/m^3 for easy transport [5], reaching a significant energy density of about 15 GJ/t [7].

For crops in tropical climates, most of the bioenergy is derived from sugar and rice. Precisely, the fibrous residue of sugar cane is often used for local electricity production in small power plants. Also, sugar cane residue is used more than wheat and corn to produce heat and electricity. For rice, the hulls are also very suitable for use in gasification plants.

To increase the energy densification of biomass, pellets are usually fabricated by applying pressure on biomass waste (mainly sawdust). Pellets are already subject to quality standards for a growing process of commercial activity (6–12 mm in diameter, 10–30 mm in length, moisture content below 10 %, ~650 kg/m^3 and ~17 GJ/t) [4]. For example, the new European standard for pellets (EN 14961–2:2011) provides three quality classes of pellets to be used in different heating systems [8]. The pellets are also easy to transport and handle, but these activities also require standardisation [8]. However, the pellets absorb moisture, which can lower the calorific value below 10 GJ/t with aging in contact with the atmosphere.

An additional option is to subject the biomass to torrefaction processes (200–300 °C) by which it is converted into a dry, hydrophobic and higher energy density (19–23 GJ/t) product [4], holding up 92 % of the energy of the raw material. Torrefacted biomass can also be converted into pellets, process that can lower its cost per energy unit. Moreover, torrefaction facilitates biomass transport and storage activities.

Another procedure to improve biomass energy density is through pyrolysis. In this process, the raw material is heated in the absence of oxygen, producing charcoal, bio-oils and biogas. The fraction of each product depends on the temperature and residence time of vapours in the process. The application of moderate temperatures (~500 °C) for 1 s is used to maximise the liquid fraction, in a process called fast pyrolysis. By contrast, the slow pyrolysis is commonly used for obtaining charcoal. The biogas produced is often used as energy input in the pyrolysis process itself. The bio-oils obtained have a calorific value of about 17.5 GJ/t, but the energy density per unit volume (20–30 GJ/m^3) doubles to quadruples that of the pellets and the product of torrefaction, although this is only yet about half the biodiesel energy density [4].

On the other hand, animal manure and debris from urban wastewater should also be considered, as they can be a major source of greenhouse gases. In some countries, these sources represent a significant percentage of methane emissions. This type of biomass energy is valued using anaerobic digestion to produce biogas in livestock farms.

In relation to renewable municipal waste, each household in the industrialised world produces about 1 t/year, with an energy content of about 9 GJ/t [1]. Currently, these products are being valued through combustion processes or anaerobic digestion, producing gas that can be used to generate heat or electricity. Also, the renewable municipal waste can be stored in impermeable disposal cells in which gases are produced naturally by anaerobic digestion, and later collected through a mesh of interconnected and perforated pipes to depths of about 20 m. The production of landfill gas per tonne of waste is estimated, in theory, at about 150–300 m^3, containing a high proportion of methane, and an energy of about 6 GJ/t of waste material [1].

3.2.4 Combustion

The direct combustion of biomass is the oldest technique used for energy recovery, but it is not very efficient (5–30 % efficiency in developing countries and 85–90 % in CHP systems [4]). The efficiency for electricity production ranges between 10 % for steam boilers with powers below 1 MW, and 40 % for >50 MW steam turbines combined with the latest combustion technology in fluidised beds [4].

Normally, the combustion of biomass requires a first step consisting in a simple physical treatment: sorting, crushing, compressing, air drying, etc. The low conversion efficiency for green biomass is partly due to the energy necessary to evaporate all water contained in the organic matter. Furthermore, biomass contains a high proportion of volatile materials that are emitted as vapours or tars (causing sparking during combustion) and requires additional energy, reducing the efficiency of the process. For this reason, the design of the boiler must ensure that these vapours cannot escape without burning and, consequently, oxygen must be provided. Such boilers are often used in plants of about 0.5–10 $\mathrm{MW_{th}}$.

Municipal renewable raw material is very heterogeneous and polluted, thus corroding and damaging the standard infrastructure, and therefore requiring strict emission controls, as well as a robust technology to enhance energy recovery. For this reason, conversion efficiencies to produce electricity are only of about 22 % [4].

A technology improvement compared to the above process is the fluidised bed combustion (FBC), which allows a larger heat transfer during combustion, and also an enhanced temperature control (the flame temperature to ignite biofuel is lower than in conventional combustion) and reduction of gas emissions (NO_x and CO). In this technique, the fuel material is cut in small pieces and placed on a limestone bed. In this way, an enhanced mixture between biomass and air is obtained during combustion, thus increasing the performance, and allowing the use of a less homogeneous biomass. The fluidised bed may be stationary or circulating.

As mentioned above, among all plants generating electricity from biomass, only 10–40 % of the fuel energy is exploited, since the rest is evacuated as heat to the atmosphere or to the cooling circuits. For this reason, it is much more efficient a simultaneous cogeneration of heat and power, and in this case the efficiency can reach 80–90 %. In CHP plants, heat can be used to heat water for district heating or industrial processes. In industrial applications, the heat is usually transferred through steam at a temperature of 130–200 °C and pressures of 3–16 bar [5]. Obtaining heat causes the electricity production efficiency to be reduced by several percentage points [4]. In the Nordic countries, there are many CHP plants, sometimes associated with paper mills, for the simultaneous production of heat and electricity from biomass.

As an alternative to conventional combustion, organic Rankine cycles are being considered. This cycle uses an organic fluid with high molecular mass, instead of steam, to recover heat from low temperature sources. The plants work with powers of 0.5–2.0 MW, achieving efficiencies of 17 % (slightly higher than with steam boilers) and lower working temperatures. However, the net efficiency, after deducting auto-consumption, is lower.

On the other hand, in a smaller range of power capacities are the Stirling engines (10–100 kW_e), whose technology is promising for domestic cogeneration. However, Stirling engines using biomass as fuel require further tests before they are introduced in the market. Electricity conversion efficiencies in these systems are in a range of 12–20 % [4].

3.2.5 Co-firing

The co-firing of biomass and coal in coal-fired power plants for electricity production can significantly contribute to reducing CO_2 emissions as it has already been proven in many installations worldwide, mostly in Europe. Typically, the proportion of biomass burned is 5–10 %, although in some plants up to 25 % has been tested [4]. Co-firing is the most efficient and economical technology for converting biomass into heat and electricity, as it can take advantage of the existing infrastructure for coal plants, and only small investments are required to feed the biomass itself. Currently, there is fully commercial technology implemented in this area, and power plants reaching 400 MW_e capacities are being planned [4].

The co-firing processes can be performed in three different ways: (1) directly, mixed with coal, being the most widely used process; (2) indirectly, where the syngas (CO, H_2, and CH_4) resulting from the gasification of biomass is burned with coal and, consequently, contamination problems are mitigated and (3) in parallel, where biomass is burned in a separate boiler, using the generated steam to power the main steam circuit of the plant.

It is important to note the following benefits of co-firing [5]: (1) reduction of CO_2, nitrogen oxide and sulphur dioxide emissions compared to fossil fuel processes, (2) lower investment costs than using specific biomass burners, (3) larger energy efficiency than in small biomass units and (4) reduction of risks associated with biomass supply shortages.

3.2.6 Gasification

In the gasification technique, biomass is partially oxidised by means of water vapour and air (or oxygen) at high temperatures (800–1,000 °C) to form syngas (mixture of CO, CH_4 and H_2), which can also be used for secondary purposes other than energy production. The gas can be used in steam boilers, gas turbines or co-firing. The process is not very efficient, since the total energy of the gasification products is lower than that of the initial biomass. However, the fuel gas produced is more versatile and less polluting. If the gasification is carried out in air, the gaseous biofuel has a calorific value of 3–7 MJ/Nm^3, and if it is carried out in oxygen, it can reach 7–15 MJ/Nm^3 [5], although the production of oxygen requires also a considerable amount of electricity. In addition, up to 20 MJ/Nm^3 can be obtained in indirect combustion processes [4], which represents 10–45 % of the heat capacity of natural gas.

The syngas can also be cleaned of particles and condensable hydrocarbons and burned in an internal gas combustion engine, providing an electricity efficiency of 22–35 %. This efficiency is slightly higher than that achieved with the steam turbines used for biomass combustion processes [4]. This efficiency can be increased up to 40 % if the syngas is burned in gas turbines [4].

3.2.7 Anaerobic Digestion

Anaerobic digestion is the biological degradation of biomass in oxygen-free environments. The main product of this process is biogas, rich in CH_4 and CO_2. The anaerobic digestion process takes place in two phases: (1) hydrolysis and acetogenesis, which converts biodegradable material into glucose and amino acids, subsequently converted into fatty acids and (2) methanogenesis from acetic acid, also producing CO_2. The two steps can be performed in a single reactor (single-step anaerobic digestion) or in two steps (two-step anaerobic digestion). The second process is more efficient but more complex and expensive.

The biogas obtained from anaerobic digestion can be directly burned in CHP systems [4] or be upgraded to meet the standards of natural gas and injected directly into pipelines. Anaerobic digestion can operate with any type of biomass that can be digested by animals (that is, except biomass from wood). The process is particularly efficient with wet biomass, sludge from sewage treatment plants, as well as in landfill cells for municipal waste storage. If the biomass used as raw material is not contaminated, the solid digestate can be also used as fertiliser, adding value to the process.

There are two proven technologies for the use of anaerobic digestion depending on the process temperature: (1) the thermophilic digestion (50–70 °C), which offers the best performance and reduction of viruses and pathogens, is mainly used in centralised systems and (2) the mesophilic digestion (25–40 °C), which requires more technology and handling of biomass.

Considering the different feedstock and processes involved, Fig. 3.4 shows a schematic overview of the pathways followed to convert solid biomass into electricity, heat and gaseous fuels.

Also, Table 3.4 shows a summary of typical power capacities and electrical and heat efficiencies for the different technologies involved for the production of energy from biomass.

3.2.8 Stages of Development

Depending on the degree of market penetration, the different technologies exposed above that are driving the production of energy from solid biomass can be considered in different stages of development (Fig. 3.5).

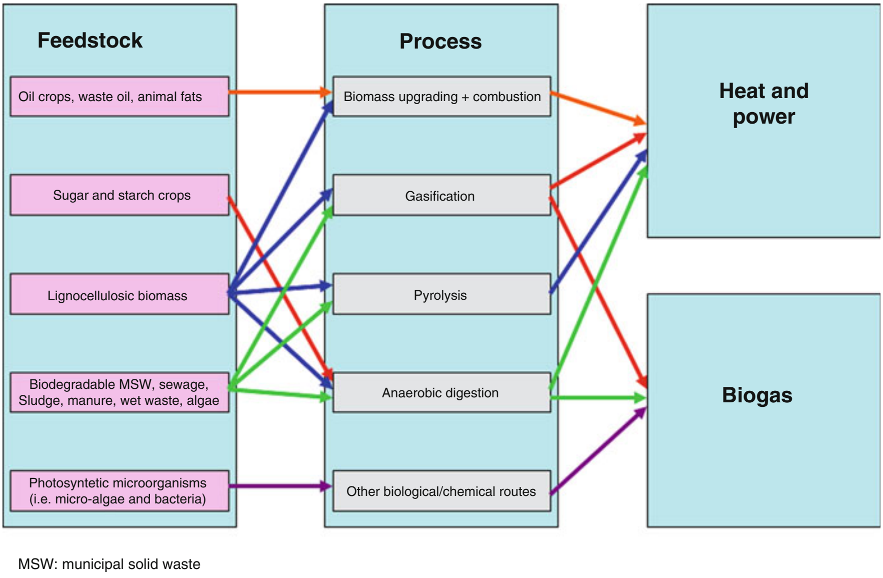
Feedstock
Oil crops, waste oil, animal fats
Sugar and starch crops
Lignocellulosic biomass
Biodegradable MSW, sewage, Sludge, manure, wet waste, algae
Photosyntetic microorganisms (i.e. micro-algae and bacteria)
Process
Biomass upgrading + combustion
Gasification
Pyrolysis
Anaerobic digestion
Other biological/chemical routes
Heat and power
Biogas
MSW: municipal solid waste

Fig. 3.4 Scheme of the different routes for the production of electricity, heat and gaseous fuels from solid biomass

Table 3.4 Typical power capacities and efficiencies for different electrical and heat technologies using biomass as fuel [5]

Conversion	Typical capacity	Net efficiency
Anaerobic digestion	<10 MW	10–15 % electrical 60–70 % heat
Landfill gas	200 kW–2 MW	10–15 % electrical
Combustion for heat	5–15 kW_{th} residential 1–5 MW_{th} industrial	10–20 % open fire 40–50 % stoves 70–90 % furnaces
Combustion for power	10–100 MW	20–40 %
Combustion for CHP	0,1–1 MW 1–50 MW	60–90 % overall 80–100 % overall
Co-firing with coal	5–100 MW existing >00 MW new plants	30–40 %
Gasification for heat	50–500 MW_{th}	80–90 %
BIGCC for power	5–10 MW demo 30–200 MW future	40–50 % plus
Gasification for CHP using gas engines	0.1–1 MW	60–80 % overall
Pyrolysis for bio-oil	10 t/h demo	60–70 %

Most of the technologies discussed in this chapter can be considered in a state of competition, although also active in the research, development and demonstration stages for reaching enhanced efficiencies and reducing costs.

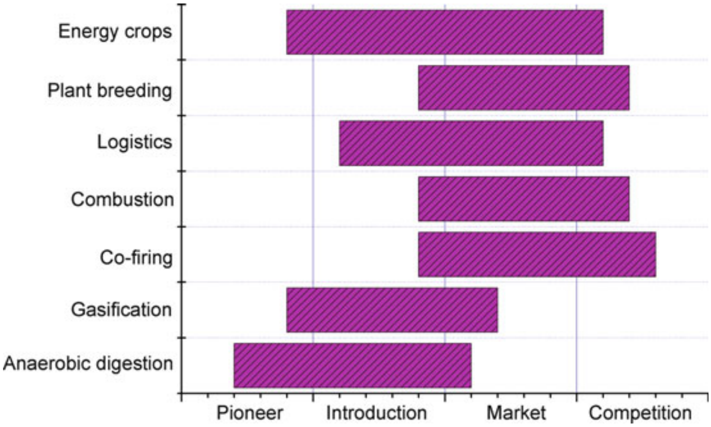

Fig. 3.5 Stage of development for each technology described in this chapter

Thus, many crop species and residues are currently being commercialised without subsidy, but further research into new crop species or genetic modification of the ones presently used is on course. In relation to cultivation techniques, the technology is in a stage of competition, but significant efforts to introduce multi-functional crops and more technology in developing countries is detected. In relation to the technology associated with harvesting, storage and transportation (logistics), it is found that they are well implemented. However, there are still opportunities for technological improvement in densification processes (pellets, torrefaction and pyrolysis) and storage, as well as in obtaining added value by implementing these processes in biorefineries.

For technologies directly related to the extraction of energy from solid biomass, co-firing processes are the most mature and competitive, but new advances are expected in indirect co-firing and co-firing in parallel. The following most mature technology is combustion, where improvements in organic Rankine cycle and Stirling engines are also expected. The gasification process can be classified as the less developed, showing BIGCC many options to improve this technology in the near term, and also by combining biomass gasification and fuel cells. In a more delayed stage, but also entering the competition phase, is anaerobic digestion, particularly in relation to the use of biogas from municipal waste landfill cells. But the anaerobic digestion to extract hydrogen from biomass is still under a very pioneering phase.

3.3 Current Costs and Future Scenarios

Unlike other types of renewable technologies with freely available resources (sun, wind, etc.), the cost of biomass typically represents between 50 and 90 % of bioenergy production (with the exception of waste). Thus, in general, the range is

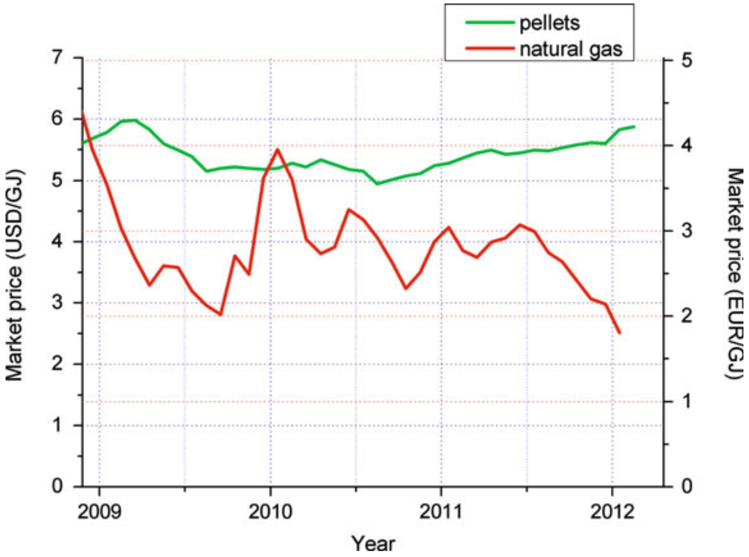

Fig. 3.6 Evolution of the market price per unit energy for pellets and natural gas (source: APX-ENDEX and CME)

usually USD 3.0–4.0/GJ (EUR 2.2–2.9/GJ) as the upper limit cost of biomass energy if strong production growth is expected. On the other hand, the use of biomass residues for other purposes, such as animal feeding, fertilisers, materials, etc., can add value and, consequently, reduce the cost of energy production, although these considerations are not quantified in this book. It should also be noted that the structure of costs largely depends upon the available infrastructure and the technology used to harvest. Moreover, the lack of transparency in some markets, especially in relation to forest resources, obstructs the resource pricing in the market [4].

Still, the forest biomass costs are well established, ranging from USD 2.3 to 6.5/GJ (EUR 1.8–4.7/GJ) for biomass delivered to an energy recovery plant [4]. These costs vary significantly depending on the country and are affected by the specific conditions of the plantation forest, distance to the energy recovery plant, techniques for collecting and processing biomass, etc.

In a detailed cost analysis of the densification processes, wood pellet costs are around USD 72–115/t (EUR 52–82/t) in Europe and USD 61–85/t (EUR 44–61/t), increasing costs a 40 % when derived from switchgrass [4]. Considering the market of the pellets in terms of price per unit energy (Fig. 3.6), except at the beginning of 2010, pellets have been more costly than natural gas for the period recorded. This scenario is expected to continue as natural gas reserves are increasing worldwide mainly due to new fracking techniques to extract it. Moreover, there is no apparent link between the price of natural gas and pellets.

Pellets costs are mainly related not only to the raw material (43 %) but also to drying (35 %), being other significant costs associated to pelletisation (7 %), personnel (6 %) and storage (3 %) [8].

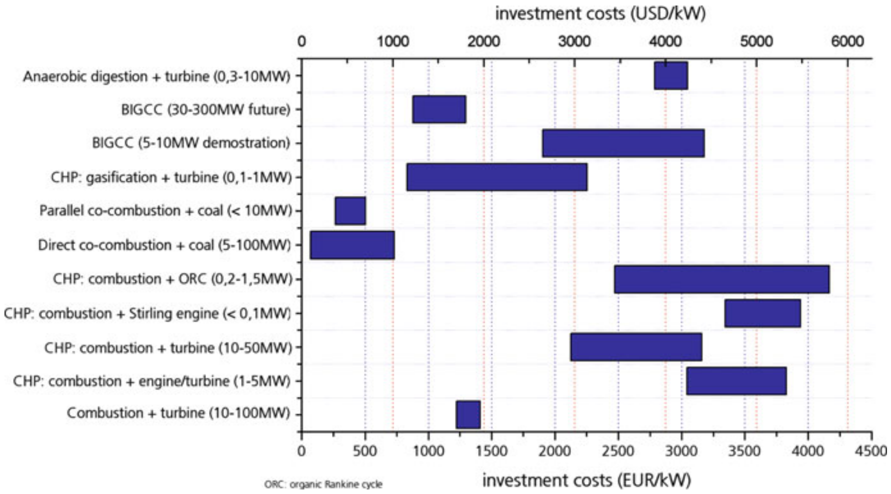

Fig. 3.7 Investment costs for different technologies for energy production from biomass [4]

Logistics costs associated to pellets subjected to torrefaction processes are estimated that can be reduced by up to a 50 %, while biomass production costs increase around a 10 %. In relation to pyrolysis, the investment costs are around USD 2,730–6,030/kWh (EUR 1,960–4,330/kW$_{th}$) for production plants with capacities of 25 MW, while production costs (excluding the cost of raw materials) are 50–100 % higher than those based on pellets or torrefaction processes [4].

The costs for the production of heat in combustion boilers using pellets as fuel are USD 11–142/GJ (EUR 8–102/GJ, with an average value of USD 37/GJ (EUR 27/GJ), which makes it competitive with fossil fuels [4]. It is expected a cost reduction of only 4–6 % in 2030 (at constant prices) as a consequence of increasing system lifetimes and efficiencies [4]. As the cost for the heating distribution network accounts for 30–55 % additional investment, high concentration customer districts and time of utilisation rates above 75 % are required to reduce this additional investment per customer.

The range of investment costs shown in Fig. 3.7 is indicative of the importance of economies of scale in energy production from biomass and the maturity of each technology (being Stirling engine, BIGCC and organic Rankine cycle the most immature). As it can be observed, the lowest costs are associated to the co-firing processes, as it capitalises thermal plants fuelled by coal. However, this process cannot be considered renewable.

The current average cost of electricity production from biomass is in the range USD 0.04–0.20/kWh (EUR 0.03–0.14/kWh). In addition, a cost reduction of only 4–6 % is expected for 2030 (at constant prices) by increasing lifetimes and efficiencies [4] as well as a reduction to USD 0.04–0.13/kWh (EUR 0.03–0.09/kWh) in 2050 [5]. Moreover, as the fuel volume demanded by the biomass power plant increases, the transport cost increases too. Consequently, a compromise between power capacity and logistics must be reached to optimise costs.

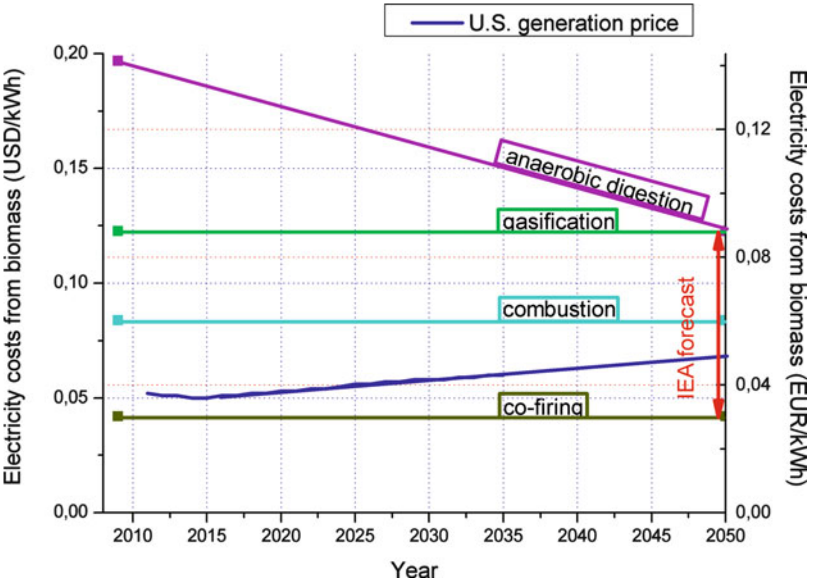

Fig. 3.8 Electricity production costs at present and those forecasted from power plants fuelled with biomass and based in different technologies. These costs are compared to the ones forecasted for US generation prices

Considering the minimal electricity cost variations from these technologies expected in the long term, we decided to assume the costs as constant (except for anaerobic digestion) to calculate the grid parities exposed below. For anaerobic digestion, we consider a linear decrease in costs because it is the most immature technology at present. This linear decrease in costs for anaerobic digestion will reach the upper range of expected costs in 2050 by the IEA [5], considering that this technology will remain more expensive over this period. Under these assumptions, the electricity production costs from biomass in 2009 and expected to 2050 are exposed in Fig. 3.8 and compared to forecasted US generation prices in constant USD and EUR per kWh.

In this sense, it is estimated that the cost of electricity production from co-firing is already below the US generation prices (Fig. 3.8). However, for the remaining technologies, no grid parity is expected in the period 2011–2050.

3.4 Energy Payback, CO_2 Emissions and External Costs

The CO_2 produced by biomass energy technologies could be considered neutral from an accounting standpoint, since the employed biomass has previously captured CO_2 from the atmosphere. However, emissions from construction and

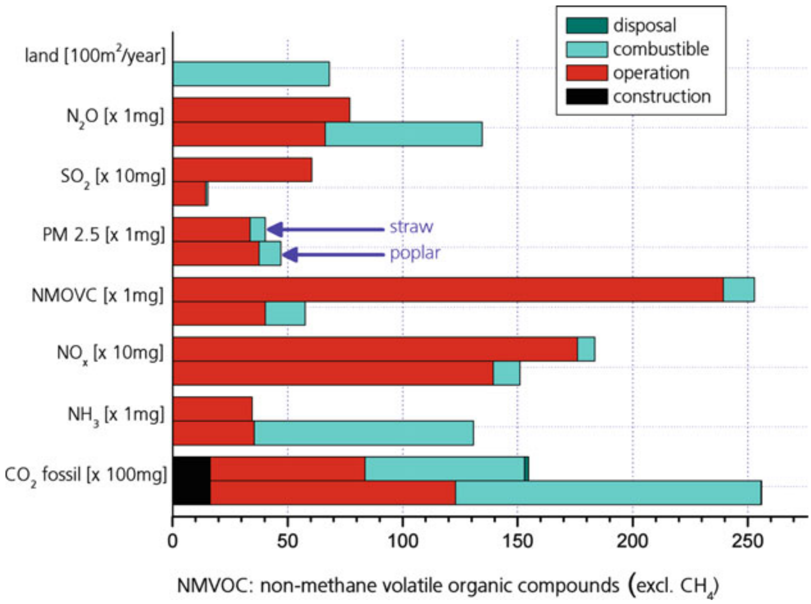

Fig. 3.9 Land emissions and land occupancy per kWh of energy produced in CHP plants [9]

decommissioning phases, as well as from biomass harvesting, treating and transporting must be also considered.

In this regard, the literature shows [9] that biomass from wood and crops burned in CHP plants (Fig. 3.9) demonstrates that CO_2 emissions are mainly originated on the biomass itself. Also, the amount of CO_2 emitted in the operation process is substantial and attributed mainly to the use of fertilisers and to transportation. In contrast, the emissions attributed to plant construction and decommissioning are under 10 % of the global emissions. Moreover, due to the production of fertilisers, large amounts of CO_2 are emitted but accompanied by ammonia and nitrogen oxide emissions.

It should be noted that this study considers that straw, as it is a residue, does neither occupy soil nor requires fertiliser for its production. In relation to transport, wood produces a larger amount of CO_2 from biomass because it has higher moisture content than the agriculture residue. In contrast, the differences in sulphur dioxide and nitrogen oxides emissions are more related to the specific composition of the biomass which, in this case, produces higher emissions than the derived from the straw. Finally, while the volume of fine particles (PM2.5) does not vary much between biomass species, production of volatile organic compounds other than methane depends on the combustion process itself.

On the other hand, although the results shown in Fig. 3.9 are for CHP technology, precise analysis will be required for the technology used since, for example, obtaining electricity from gasification emits less CO_2 than from combustion

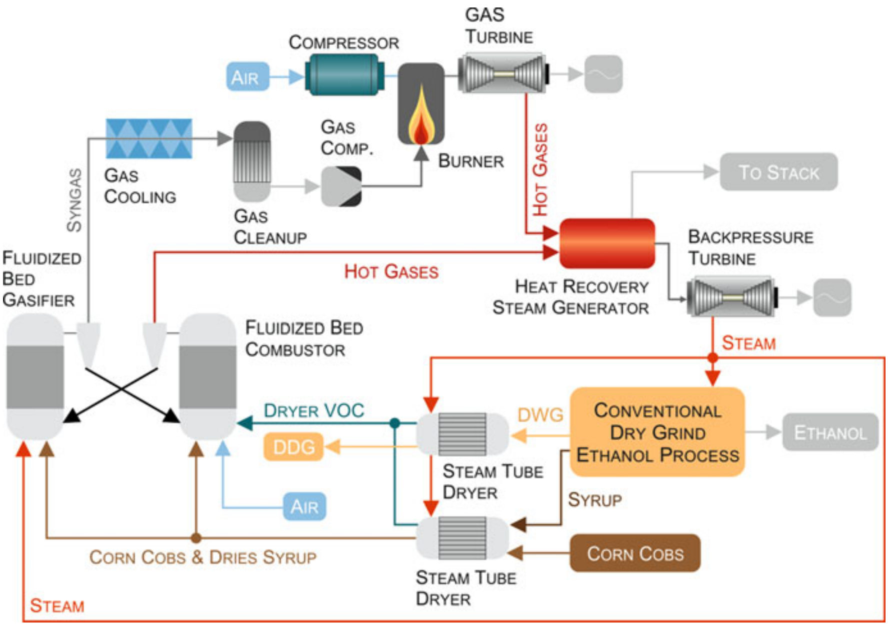

Fig. 3.10 Scheme of a BIGCC plant to produce heat and electricity from the biomass used in an ethanol production plant [15]

processes [4]. Other aspects to be considered for a detailed analysis may be related to the scale of the plant, co-products, compensating fertilisation and time at which the environmental impact occurs.

In a recent LCA study [10], different biomass plants for producing heat and/or power have been evaluated and compared with reference fossil energy systems likely to be displaced by the bioenergy system. In the cited case studies, bioenergy systems reduce GHG emissions by between 18 and 128 % compared to their counterpart fossil reference systems, but it is difficult to generalise (GHG emission reductions above 100 % mean that the involved process acts as GHG sink). Also, it is concluded that GHG mitigation is larger when biomass is used for heat and electricity applications rather than for liquid transport fuels.

Also, biomass energy production associated with the CCS technology (Chap. 17) can act as a negative CO_2 emitter, as biomass captures CO_2 from the atmosphere and is then stored. For this reason, it is expected that more rigorous studies will consider and even distinguish between different CCS technologies in the future.

Finally, the energy payback ratio using biomass as solid fuel is estimated to range between 4 and 16, while external costs are around USD 4.80 cents/kWh (EUR 3.45 cents/kWh) [11].

3.5 Future Technology Trends

3.5.1 Energy Crops

The general trend, towards the future, is on increasing biomass production for energy supply. This biomass will be mostly based on lignocellulosic crops, able to grow in poor soils and adverse climatic conditions. Lignocellulosic crops have also the advantage of requiring fewer amounts of fertilisers than food-oriented biomass.

Similarly to food crops, research on the selection of appropriate genotypes is also advancing on energy crops to enhance energy production per unit area and to minimise water requirements. The natural mission of trees and plants on Earth, after million years evolving, is their survival but not to serve as energy resources. Consequently, genetic engineering can be oriented to enhance the potential of some biomass species as energy resources. These genetic engineering activities for energy crops should be not so affected by environmental concern as for food crops. On the other hand, genetic engineering for enhancing energy potential of biomass is an alternative to the most common genetic activities, focused on achieving superior resistance to herbicides, pesticides and insects [4]. Thus, because of its interest, research in energy crops will increase because is still in the initial stages, and also due to lack of experience on crop plants genetically modified and introduced in forest, shrubs, bushes, grass, etc.

It is also necessary to study the parameters affecting the productivity of biomass, since it is susceptible to the volatility inherent to biological production (due to seasonal variations and weather conditions). Inadequate control of these parameters can produce significant variations in the quantity of production, quality and, consequently, price. Price volatility is evidently an important drawback that any renewable energy should avoid in order to compete against fossil fuels.

Finally, it is also necessary to study the effects of climate change on energy crops. In many areas where it is now adequate to cultivate specific energy crops, expected climate changes could also force a change in crop species to maintain energy production from biomass.

3.5.2 Cultivation Techniques

There is great interest to cultivate biomass in multi-functional locations. Thus, choosing optimal locations, design, management and integration of production systems, extra environmental services can be offered and thus have a higher added value to the production. Also, it is expected to recover marginal or degraded soils for energy crops. On the other hand, it is expected to improve productivity in developing countries, which may cover increases in demand for energy crops [4].

Research efforts are also on course to avoid stress in water resources or biodiversity loss associated to increasing production of energy crops. On the contrary, it is expected that these crops may help to improve conditions and fertility of degraded soils, preventing erosion, when the most suitable species for each zone are selected.

3.5.3 Harvesting, Storage and Transportation

Future trends are oriented to create standards for crops and also for new lignocellulosic energy crops to be perennial and, consequently, not generating inflationary pressures in the food industry, thus ensuring its permanent access to the market. Perennial lignocellulose would diminish biomass storage costs and degradation processes associated to stored biomass.

There is also the need to develop multi-product biorefineries, capable of increasing the added value of transforming the raw material. This strategy can reduce the power generation costs from biomass very substantially.

As it is known, biomass has a low energy density compared to fossil fuels and also high humidity (may reach 55 % in weight). Consequently, it is necessary to improve densification technologies (pellets, chipping, baling, bundling, pyrolysis and torrefaction). These densification technologies can reduce transportation costs significantly and increase production plant sizes [4], and therefore reduce infrastructure costs to produce energy from biomass per unit of energy produced. As it is known, increasing the size of the plants using biomass reduces costs but, on the other hand, increases biomass demands, also increasing transport costs (from increasingly distant places). Therefore, it is necessary to reach an optimal compromise between plant size and logistics to properly size the plant.

Storage techniques are also improving depending on the type of biomass, since the durability of the stock depends on the specific energy crop considered. In addition, low biomass humidity introduces self-ignition and self-heating risks. Consequently, it is recommended to avoid the storage and transportation of large volumes and mixing of different types of biomass.

In pellets, it is necessary to study alternative raw materials and processes to increase stability and abrasion resistance, to reduce the emission of dust in household manipulation [4] and to prevent the danger of off-gassing (primarily CO, CO_2 and CH_4) from pellets decomposition over time [8].

Regarding pyrolysis, it is especially important the stabilisation of the produced bio-oils, and to reduce their water content, corrosive nature, viscosity, as well as minimising the large number (over 300) of chemicals that compose them. In this sense, it is necessary to better understand the type of thermal reactions and the role of the catalysts for improving the processes related to bio-oils production. Also, the solid product of pyrolysis can be used in a co-firing process to provide energy to the proper pyrolysis.

Finally, for renewable municipal waste, it is necessary to improve the waste sorting processes to obtain competitive energy costs. Currently, the raw material is very heterogeneous and contaminated, requiring strict emission controls and robust technologies to obtain energy from this resource.

3.5.4 Combustion

An option that is being proposed is the conversion of CHP systems into trigeneration systems, also acting as cooling systems by applying absorption processes (Chap. 13). As the heating demand varies seasonally, the addition of cooling allows the heating demand to be more stable over the year and results in an increase of the profitability for the biomass conversion system. For electricity generation, smaller and less expensive CHP systems should be developed in order to enhance adaptability to local biomass resources.

Also, it is necessary to adapt combustion systems to specific industrial sectors, mainly in terms of temperatures reached, and the quality of the gas ejected from the combustion process. Moreover, it is necessary to improve the efficiency of organic Rankine cycles and Stirling engines. For the latter, it is estimated that the power conversion efficiency could reach up to 28 % in 150 kW engines. However, additional R&D activity is needed, as these processes are not mainly oriented to the production of power. Moreover, it is necessary to improve the reliability and costs of these processes.

Besides, new combustion boiler prototypes are demanded, offering higher efficiency, smaller size, allowing burning biomass other than wood (pruning waste, crop residues, etc.) and controlling emissions of polluting gases, especially NO_x. In this area, research modelling reactive boiling ejection of non-volatile compounds in the product stream (particularly those that enter the gas phase) should lead to better control over emissions.

For energy recovery from municipal waste, it is estimated that technological advances could increase process efficiency from 22 % to 28–30 % applying new generation power plants [4].

Other aspects that need improvement are the supply and storage of raw materials for the combustion process, as well as to avoid fluctuations in humidity and contamination by heavy metals. Humidity and biomass contamination from the combustion plant have a substantial impact on air pollution and corrosion.

3.5.5 Co-firing

At present, the proportion of biomass used in co-firing systems has reached about 10 %, but systems reaching up to 20 % are being tested. However, in this case, the resulting abundant ash should be conveniently treated, since it can be deposited on the burner and the catalyst, reducing the efficiency of the process. It is also necessary to consider how to mitigate the harm caused by the coal–biomass mix to the exhaust gas filtering systems. Also, co-firing systems that can be fed with different biomass species, specific heating temperatures and processing techniques are under research.

The electricity production efficiency usually achieved in co-firing is 20–25 % [12], but R&D activities are trying to increase it through several procedures.

One consists, for example, in improving the quality of the refractory materials of the furnace walls to increase heat insulation and, therefore, reaching higher gas temperatures. Also, the reactor design and processing of biomass is being modified to reach the most complete combustion possible. Efficiencies around 50 % have been reached by indirect co-firing processes in IGCC systems [4].

Finally, the co-firing accompanied by a previous pyrolysis of biomass could be an appropriate route for cost reduction, mainly in places where the biomass production is located at large distances from coal-fired power plants. Also, large fluidised bed supercritical boilers, with power generation efficiencies as high as 50 %, could be based on co-firing processes in the future [5].

3.5.6 Gasification

The economic viability of biomass gasification is not yet proven on a large scale, but there are currently several R&D programmes trying to advance on gas turbines powered by biomass. The most popular are the BIGCC systems. The interest in these systems surges from the fact that up to 85 % of energy from biomass is recovered in gasifiers by means of partial oxidation in oxygen or a water vapour environment. This fact, together with the use of combined cycle technology gives BIGCC a significant potential advantage over simple combustion.

A very important aspect being investigated is related to the elimination of pollutants generated by the treatment of biomass (particulate, ash, ammonia, sulphides, etc.). These pollutants cause corrosion and deposits on the turbine blades. Finally, BIGCC can be very interesting for the production of energy, both thermal and electrical, in ethanol production plants. Another option that is being tested is the use of the liquids produced in the gasification process to obtain liquid fuels and other materials, synthesised in biorefineries.

Another option consists in the synthesis of hydrogen from syngas for use in integrated fuel cells, with an estimated electric conversion efficiency of 50–55 % [4], but this technology requires further development effort (see Chap. 14). In addition, from syngas, methane-rich gas can be obtained, known as synthetic natural gas, or the syngas can be converted into a liquid fuel through a Fischer–Tropsch process (see Chap. 4).

Finally, it is necessary to study in more detail the moisture influence to the biomass gasification process and the optimisation of the cleaning processes of the reactors.

3.5.7 Anaerobic Digestion

The first objective for anaerobic digestion is to improve the biomass pretreatment to reduce fermentation times. Other objectives are (1) reducing costs, (2) increasing reliability of the technology and (3) improving the cleanliness of the biogas (especially the very corrosive H_2S). These improvements can be reached by ultrasound treatments or enzymatic reactions, currently in the R&D phase.

Other technology trends are related to the improvement of both the pretreatment processes and the selection of raw materials. The objective of this selection is to remove contaminants and to transform the digestate produced in anaerobic digestion into a nutrient for various applications. This strategy could be less expensive than cleaning the polluted digestate inside the anaerobic digestion system.

Improving biogas recovery from the anaerobic digestion of organic municipal waste is also a main research area. The technology trends are focused on reducing emissions of greenhouse gases, primarily methane, as it is much more harmful than CO_2 in causing greenhouse effects.

Finally, several research groups are very active in the direct production of hydrogen based on the anaerobic digestion of biomass in the so-called microbial fuel cells [4]. The hydrogen synthesis process has already been achieved, but demonstration plants are needed to further test this technology (see Chap. 5).

3.6 Pre-production Highlights 2009–2011

3.6.1 The World Largest Biomass Power Plant [13]

The largest power plant powered by biomass will be located in Port Talbot (Wales). With a capacity of 350 MW, it will be able to provide electricity to nearly half a million homes. The plant, designed by Preenergy Power has required an investment of EUR 650 million, and construction work is not expected to start before the end of 2011. The plant will be powered by wood chips imported from USA. The biomass plant in Wales is expected to reduce CO_2 emissions to a fifth of the emissions from a conventional coal plant. The British Environment Agency has asked the company certificates to ensure that all biomass used should come from renewable resources. Some concern about air quality and health risks are expressed by opponents.

3.6.2 New Strategies to Increase Biogas Production from Wastewater [14]

The company GENeco, a subsidiary of the British company Wessex Waters, instead of managing manure wastewater at room temperature, heats it for a few days at 40 °C and then transfers the fermented liquid to a second tank with a temperature 5 °C cooler. Then, at each stage, different bacteria can act more efficiently, thus increasing by 30 % the production of methane. In addition, there are other options emerging from different research centres such as (1) mixed pumping to accelerate the separation of methane and the movement of bacteria and (2) the use of ultrasounds for a more effective decomposition of waste. These strategies increase the methane production by about 13 %, although in the latter case the energy balance is still negative.

3.7 Innovation Highlights 2009–2011

3.7.1 BIGCC to Produce Electricity and Heat in Ethanol Plants [15]

Scientists at the University of Minnesota (USA) have experimentally demonstrated that the BIGCC technology can be used to generate heat and electricity at very low costs in ethanol production plants. These plants use corn cobs to generate syngas in a gasification process (Fig. 3.10). It has been found that an ethanol plant producing 190 million litres annually is able to continuously generate power by about 30 MW. The energy generated is used for the production of ethanol, resulting about three times cheaper than conventional ethanol produced from natural gas.

3.7.2 Electricity Production from Anaerobic Digestion in Microbial Fuel Cells [16]

Specific anaerobic bacteria can generate electricity by means of so-called microbial fuel cells following a procedure analogous to the anaerobic digestion described in Sect. 3.2.7. Scientists at the Center for Nanotechnology at the University of Cornell have developed fuel cells made by silicon microelectronics lithography and based on this technology. At the anode of the battery, the biofuels are placed (organic waste, carbohydrates, manure, etc.) and they are oxidised anaerobically by micro-organisms, producing protons and electrons. Then, the electrons are transferred to the cathode through an external circuit generating an electric current. Among the bacteria that show a higher electrochemical activity are the *Shewanella putrefaciens* and the *Aeromonas hydrophila*.

3.7.3 Using Charcoal Production to Store CO_2 and Produce Heat [17]

The use of charcoal in rural areas was discussed at the 2009 meeting of the North American Biochar Conference. In this meeting, advantages were provided about using the pyrolysis process to meta-stabilise the CO_2 fixed during the growth of different plant species as charcoal in agricultural areas. This process may introduce many advantages such as: (1) carbon capture and storage; (2) crop production improvement by buried charcoal and (3) production of heat, syngas and heavy oils that can be considered as energy resources. In addition, soils containing

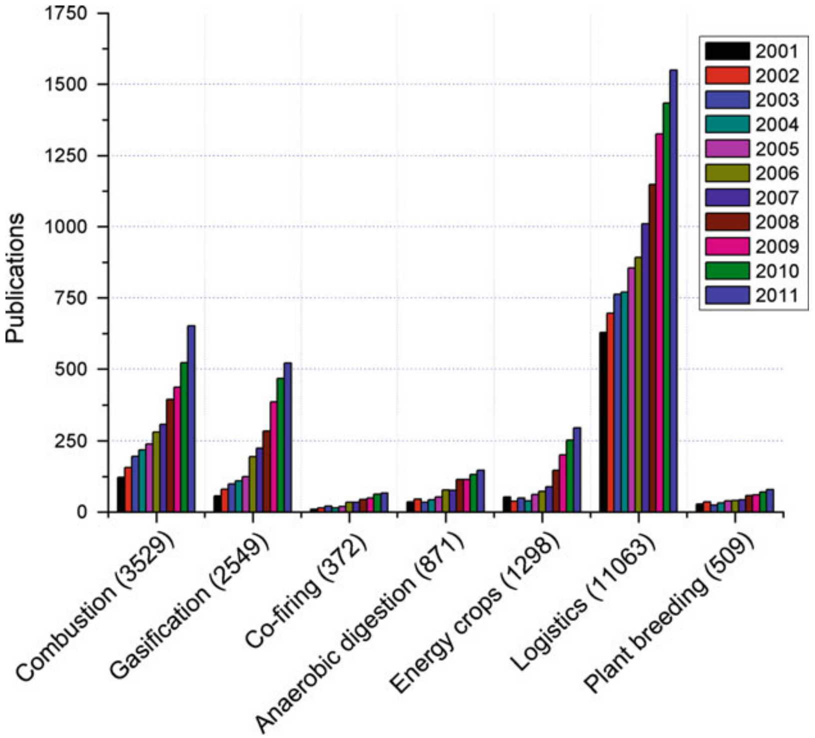

Fig. 3.11 Number of scientific publications during the period 2001–2011 for different technologies involved in energy production from biomass [18]

charcoal emit less nitrogen oxide and methane (a potent greenhouse gas) because of its catalytic properties for these gases, thus reducing their impact on climate change. It is estimated that through this process up to 20 % of CO_2 emissions could be avoided, although the calculation models still require some adjustments. However, some problems could arise if this technology induces deforestation to produce biomass to be later converted into charcoal.

3.8 Statistics of Publications and Patents

Figure 3.11 shows the number of scientific publications during the period 2001–2011 for different types of technologies involved in energy production from biomass [18].

According to Fig. 3.11, it is found that the main research activity is on logistics, i.e., related to the harvesting, storage and transportation of biomass. This can be interpreted as a consequence of the need to reduce costs and CO_2 emissions in the process related to energy production from biomass. Research areas corresponding to energy crop species are also rising in activity, but they are far below logistics.

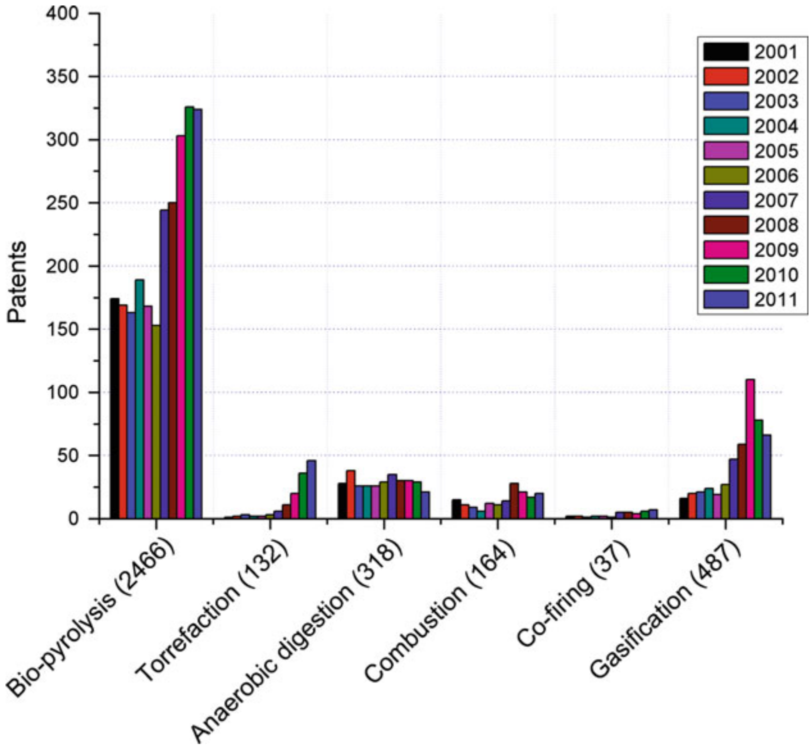

Fig. 3.12 Number of patents during the period 2001–2011 for different technologies involved in energy production from biomass [19]

Research activity related to farming techniques is also rising, but the number of publications is low compared to logistics and crops.

In relation to energy production technologies, the largest activity is detected in combustion processes, but the gasification technology is also rapidly growing. These results are attributed to the central role that BIGCC systems are expected to play in the future. Anaerobic digestion lies not only far below combustion and gasification but also with an upward trend. Finally, research activity in co-firing is the lowest and attributed to its lack of attractiveness as it combines biomass and coal combustion. Co-firing cannot be considered a clean energy technology and is not attractive for future energy models trying to mitigate the emission of GHG.

In relation to the evolution of biomass technology patents [19], our analysis has been focussed on technologies for the increase of energy density of biomass, and those to produce energy from biomass. This is because we consider that patents related to logistics, crops and farming techniques are more extensive and not only related to energy production from biomass.

From Fig. 3.12, it can be observed that the main area for patent production related to energy densification is bio-pyrolysis. In our opinion, this is due to the fact that the pyrolysis process is rich in products, as exposed above, offering large opportunities for manufacturing activities in biorefineries. Other processes, such as torrefaction and pelletisation, are very specific and oriented.

In relation to energy production from biomass, the main area for patent production is the gasification technology. We attribute this result to the expectation derived from the introduction of BIGCC systems to produce energy. This expectation also may be influencing the development of anaerobic digestion, as the second energy production technology from biomass in number of patents. On the third place is combustion, as this is a more mature technology. Finally, patent activity in co-firing is very low, and this is also attributed to its lack of attractiveness as explained above.

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